A climatology of flow and turbulence at 190 m above central London

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1. Introduction

❑ It is essential to understand the flow and turbulence characteristics in urban areas in order to provide better predictions for thermal comfort and human exposure to hazardous materials (e.g. Wood *et al.* 2009).
❑ Flow in and above an urban area is complex because of the influence of buildings, the urban heat sources and the unsteady meteorological conditions.
❑ The purpose of this poster is to examine the validity of surface-layer and mixed-layer similarity relationships (based on scales like $u*$, w_*, L and z_i) using sonic anemometer data at 190 m above ground in London.

2. Experimental design & site description

❑ Greater London has a diameter of order 40–50 km (Figure 1). Based on spatial averages at 1 km resolution (Evans 2009), mean building heights peak at 26.5 m with a mean of 8.8 ±3.0 m within 1–10 km of the tower (and beyond 10 km, most of suburban Greater London is 5.6 ±1.8 m). Hence, the sensor is ~ 22 times the mean building height upwind of the tower (1–10 km). Displacement heights within 10 km of the BT-tower were calculated as 4.3 ± 1.9 m (Padhra 2009).
❑ A sonic anemometer was mounted at 190 m on the BT-tower in west-central London (51.5215°N, 0.1389°W; Figure 1). It was clamped to an open lattice scaffolding tower of 18 m height on top of the main structure. The data analysed here were collected from October 2006 to May 2008.
❑ A 30-minute streamwise rotation was applied, using the double-rotation method (Wilczak *et al.*, 2001). Following quality assurance (including removal of spiked data), the original data were reduced to 6446.5 hours. Spectra of anemometer data (normalized spectral density, fS, against natural frequency, f) were produced. The peak frequencies, f_{max}, in the spectra of horizontal wind were calculated by finding the frequency at maximum of fS. Using Taylor's frozen turbulence hypothesis, a peak wavelength was calculated (2 hours' data were used for each estimate of peak wavelength) which was related to mixed-layer depth. During only 0.3 % of data-periods was $z/z_i < 0.1$, hence the sensor was often located well within any daytime convective boundary layer.

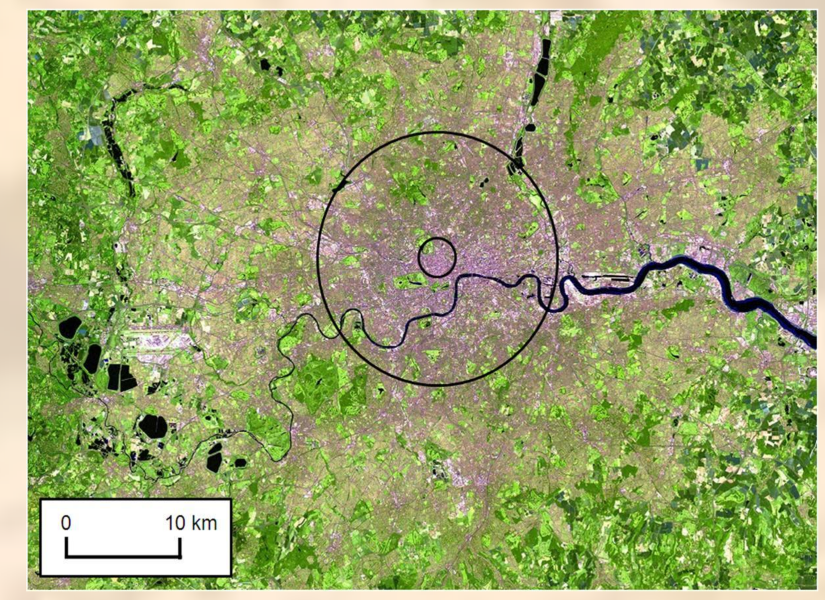

Figure 1: Satellite photograph of London. Rings are of radius 1 and 10 km centred at BT-tower. Image is courtesy of the Cities Revealed dataset on LandMap.

3. Results & discussion

Climatology:

❑ South-west was the most frequently occurring wind direction (Figure 2) and the least frequent wind direction is from the south-east.
❑ Wind speed covers a wide range of speeds from 0–20 m s^{-1} with a mode of approximately 7 m s^{-1}.
❑ Stability was calculated as $\zeta = z'/L$, where the Obukhov length was calculated as $L = -u_*^3/(\text{kg/T } \overline{w'T'})$ and u_* is a scale velocity (local friction velocity) and $z' = z - z_d$ = 190 m – 4.3 m).
❑ The number of unstable cases is about three times the number of the stable cases (Figure 3). The number of unstable cases at night-time is almost equal to their number during daytime. We also observe some stable periods during daytime.
❑ The relationship between the momentum flux and the mean wind speed can be described by the drag coefficient, $C_D = (u_*/U)^2$, where U is the mean wind speed. In neutral stratification, C_D was greater for flow from the east and south-east sectors than for the other sectors (Figure 4). This means that the south-east upwind sector was rougher than the others.
❑ Values of C_D were also derived from morphological methods (Padhra 2009) averaged on a 1 km grid size in London (assuming a logarithmic wind profile). For comparison with tower data, the relevant upwind source areas were calculated using the flux source-area model developed by H. P. Schmid to give upwind distances between 1 and 10 km (Schmid 1997; http://www.indiana.edu/~climate/SAM/).

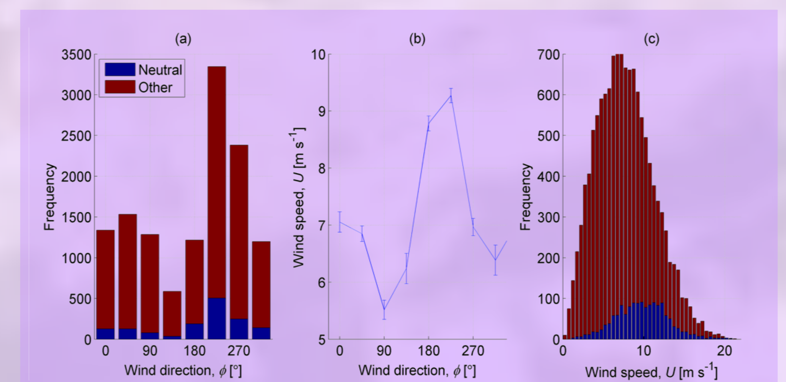

Figure 2: Frequency distributions of wind speed and directions (neutral defined as $|\zeta| < 0.1$), and mean wind speeds in each 45° sector.

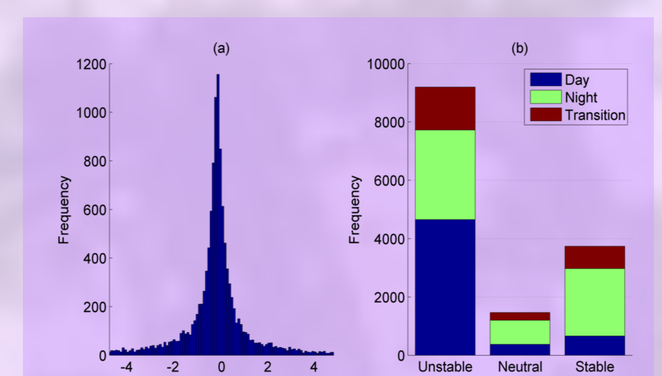

Figure 3: Frequency histogram of stability (left), and categorized by period of the day (right). Transition was defined by two hours centred on sunrise/sunset.

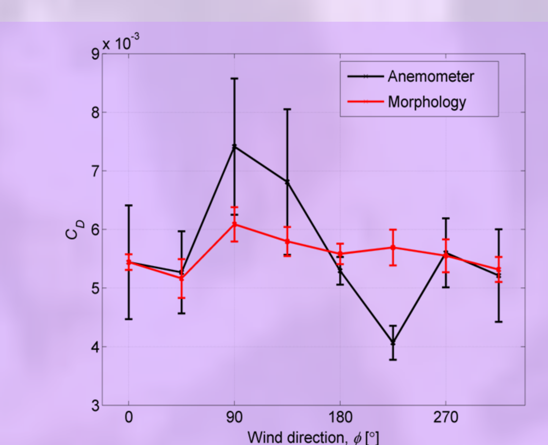

Figure 4: Dimensionless drag coefficient, C_D, as a function of upwind sector (and within the range 1–10 km upwind of the tower). Confidence intervals (95 %) of the means are shown. (Data sub-sampled for neutral and $U > 1$ m s^{-1}.)

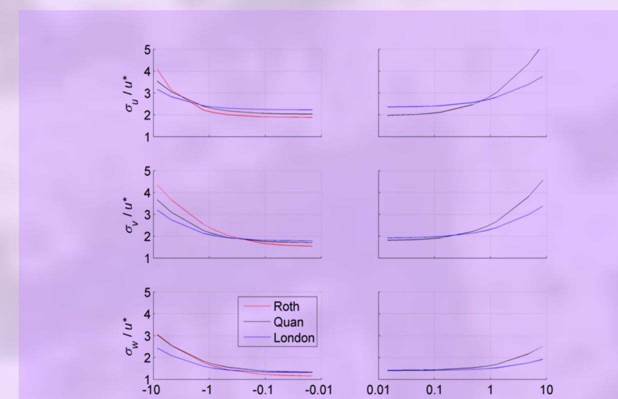

Figure 5: Normalized standard deviations of u, v and w as a function of stability ($\zeta = z'/L$). Formulations are from Roth (2000), Quan and Hu (2009) and London (fitted for $|\zeta|$ from 0.01–10). Data sub-sampled for $U > 1$ m s^{-1} and sensible heat flux > 10 W m^{-2}.

Wind variances

❑ Firstly, surface layer scaling is used to analyse the data (Figure 5). The σ_i/u_* values for the neutral conditions were found to be 2.3, 1.85 and 1.35 for u, v and w, respectively. These values are quite similar to those for flat terrain.
❑ Secondly, data are scaled with the mixed-layer formulations. One method to estimate z_i is to use the peaks in the spectra of u and v (Liu and Ohtaki 1997). The mixed-layer height and corresponding w_* were calculated using 2 hours' data. The measured $(\sigma_w/w_*)^2$ are plotted against z'/z_i for strongly unstable conditions ($\zeta < -0.5$) (Figure 6) and compared with Sorbjan (1989) and Wilczak *et al.* (1986). The surface heat fluxes were estimated assuming a linear relationship between heat fluxes and height (using a slope of 1.2, Stull (1988: p.370) with the data from 190 m. The new σ_w^2/w_*^2 curve shows the same structure as found by other investigators and peaked at a lower height (around 40 % of the mixing-layer depth), which is quite similar to the value found by Caughey and Palmer (1979) over flat terrain.
❑ The standard deviation of the longitudinal (Figure 6b) and lateral components (not shown) were similar. Almost no change with height was observed. A similar profile was measured in Minnesota (Caughey and Palmer, 1979) but the London data have increased values.
❑ The narrow scatter of the vertical wind component statistics over London with the mixed-layer scaling might be due to a corresponding increase in the sensible-heat flux (including anthropogenic heat) at the surface expected/observed in urban areas and possibly also due to higher boundary layer heights.

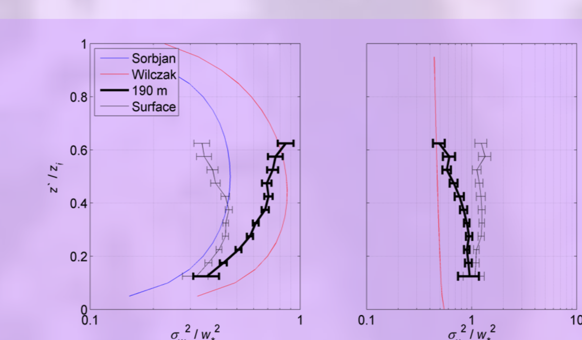

Figure 6: Normalized standard deviations of w *and* u as a function of height; data were sub-sampled for cases of stronger convection ($\zeta < -0.5$). Mixing-layer depth, z_i, was calculated as an arithmetic mean of the values estimated from both u and v spectra. A profile based on the estimated surface heat flux is also included. Confidence intervals (95 %) of the means are shown. Data sub-sampled for daytime, $U > 1$ m s^{-1} and sensible heat flux > 10 W m^{-2}.

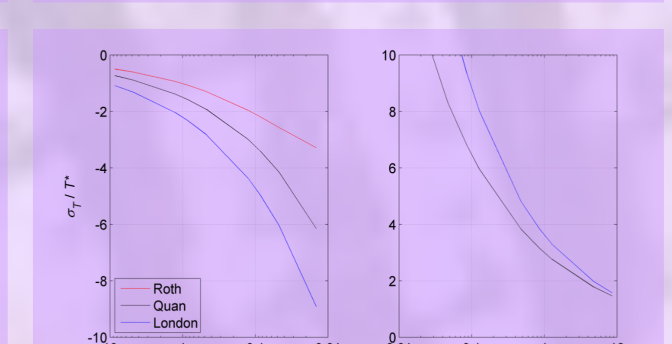

Figure 7: Normalized standard deviation of temperature against stability ($\zeta = z'/L$). Formulations are shown from Roth (2000), Quan and Hu (2009) and London (fitted for $|\zeta|$ from 0.01–10). Data sub-sampled for $U > 1$ m s^{-1} and sensible heat flux > 10 W m^{-2}.

Temperature variances

❑ Similar to the surface layer relationships of standard deviation of wind, several formulations have been suggested for the σ_T/T_* (Figure 7).
❑ Using the mixing-layer similarity approach we plot σ_T/θ_* as a function of nondimensionalized height (Figure 8).

Turbulent transfer efficiency

❑ Turbulent correlation-coefficients are a measure of the efficiency of turbulent transfer, (e.g. Roth 1993).
❑ During very unstable conditions the momentum transfer is low (Figure 9) and the heat transfer is high. Whereas in neutral conditions the momentum correlation coefficients are about 0.3 and 0.1 for and respectively.

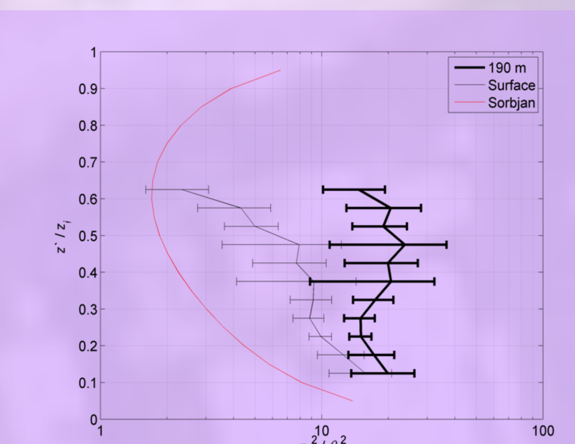

Figure 8: Normalized standard deviations of temperature as a function of height; data were sub-sampled for cases of stronger convection ($\zeta < -0.5$). Mixing-layer depth, z_i, was calculated as an arithmetic mean of the values estimated from both u and v spectra. A profile based on the estimated surface heat flux is also included. Confidence intervals (95 %) of the means are shown. (Data sub-sampled for daytime, $U > 1$ m s^{-1} and sensible heat flux > 10 W m^{-2}.

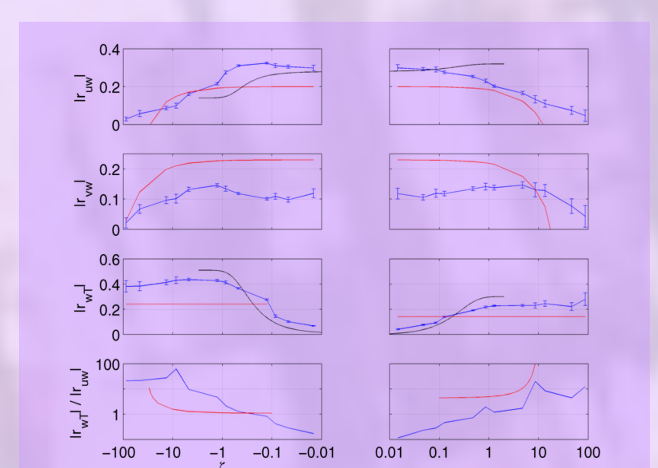

Figure 9: Momentum (top four subplots) and heat flux (next two subplots) correlation-coefficients, and the ratio between heat flux and momentum transfer (lowest two subplots) as a function of stability ($\zeta = z'/L$). Confidence intervals (95 %) of the means are shown. Data sub-sampled for $U > 1$ m s^{-1} and sensible heat flux > 10 W m^{-2}. Curves for comparison in black (Filho et al. 2008) and red (Aljiboori) 2008.

4. Final remarks

❑ Similarity relationships are an appealing tool to compare meteorological data from different sites and are used in parameterizations of momentum, mass and energy in the atmospheric boundary layer.
❑ Normalized wind standard deviations follow MOST well in both unstable and stable stratification when all variables are local. The normalized temperature variances show more scatter but still collapse as a function of the stability parameter, ζ.
❑ Using z_i (the mixed layer height) for the convective length-scale, show that the normalized (with local w_*) vertical and horizontal wind variances behave similarly to observations in rural and/or flat terrain. The same applies to the normalized temperature variance.
❑ The momentum turbulent correlation-coefficients are small under strong stratification but increase quite steeply toward neutral conditions. The heat transfer correlation coefficient is high and constant for $|\zeta| > 0.1$.
❑ BT-tower data analysis implies that locally-normalized turbulence at high levels above a large urban area (e.g. London) behaves not dissimilar to that above flat/rural terrain.

Acknowledgements

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The work in this poster is due to be submitted to Boundary-Layer Meteorology in late 2009.

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